

ANOMALOUS COOLING OF THE MASSIVE WHITE DWARF IN U GEMINORUM FOLLOWING A NARROW DWARF NOVA OUTBURST *

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Abstract

We obtained Hubble GHRS medium resolution (G160M grating) phase-resolved spectroscopic observations of the prototype dwarf nova U Geminorum during dwarf nova quiescence, 13 days and 61 days following the end of a narrow outburst. The spectral wavelength ranges were centered upon three different line regions: N V (1238Å, 1242Å), Si III (1300Å) and He II (1640Å). All of the quiescent spectra at both epochs are dominated by absorption lines and show no emission features. The Si III and He II absorption line velocities versus orbital phase trace the orbital motion of the white dwarf but the N V absorption velocities appear to deviate from the white dwarf motion. We confirm our previously reported low white dwarf rotational velocity, $V \sin i = 100 \text{ km s}^{-1}$. We obtain a white dwarf orbital velocity semi-amplitude $K_1 = 107 \text{ km s}^{-1}$. Using the γ velocity of Wade (1981) we obtain an Einstein redshift of 80.4 km s^{-1} and hence a carbon core white dwarf mass of $\sim 1.1 M_\odot$. We report the first subsolar chemical abundances of C and Si for U Gem with C down by 0.05 with respect to the Sun, almost certainly a result of C depletion due to thermonuclear processing. This C-depletion is discussed within the framework of a weak TNR, contamination of the secondary during the common envelope phase, and mixing of C-depleted white dwarf gas with C-depleted matter deposited during a dwarf nova event. Remarkably the T_{eff} of the white dwarf 13 days after outburst is only 32,000K, anomalously cooler than previous early post-outburst measurements. Extensive cooling during an extraordinarily long (210 days) quiescence followed by accretion onto an out-of-equilibrium cooled degenerate could explain the lower T_{eff} .

1. Introduction

The dwarf nova U Geminorum undergoes both wide (~ 14 days) and narrow ($\sim 4\text{-}7$ days) outbursts during which it is expected that differing amounts of mass and angular momentum accretion occur onto the white dwarf. Therefore in a continuing effort to elucidate the tangential accretion physics, in particular the actual mechanism of accretional heating, e.g. shear mixing, compression and irradiation, it is of interest to compare the response of the white dwarf to outbursts of different lengths, for example, a wide outburst versus a narrow outburst. The differential heating effect of a normal outburst versus a superoutburst has already been demonstrated for the case of the white dwarf in VW Hydri (Gänsicke & Beuermann 1996; Sion et al. 1996). We obtained high resolution GHRS observations of U Gem during the quiescence following a narrow outburst which allow us to do just that. Moreover we obtained these spectra at the orbital quadratures to maximize the velocity displacements of the lines, delineate different regions of line formation and estimate the mass of the white dwarf from its gravitational redshift. In this paper we report the results of our experiment and interpret the results comparatively with the results and predictions of earlier investigations of U Gem.

2. HST GHRS Far Ultraviolet Observations

Upon notification of the onset of an outburst of U Gem by AAVSO observers, we obtained two sets of GHRS observations of U Gem during the following quiescence, the first set on 1995 October 10 (Obs1) and the second set on 1995 November 27 (Obs2). The temporal placement of the observations with respect to the narrow outburst is shown in figure 1 where we present the AAVSO light curve data for the outburst and the following quiescence. The first set of observations took place 13 days after outburst while the second

dataset was obtained 61 days after outburst. The observations for both observations were carried out in the ACCUM mode with the D2 detector of GHRS and the G160M disperser. Three wavelength regions were covered by the observations: the N V region (1219Å to 1255Å), the Si III region (1269Å to 1304Å) and the He II region (1616Å to 1648Å), with a resolution of 0.25 Å. The wavelength scale has an accuracy of ~ 0.10 Å. Since the objective of our line formation study was to delineate the white dwarf photosphere in quiescence and obtain maximum velocity displacement and mass information for the white dwarf, the observations were obtained close to the quadrature points of the orbit.

Table 1. HST GHRS Observations of U Gem

Quiescence Obs. No. 1: 95/10/10						
Ion	Start Time	T _{exp} (s)	Start (MJD)	Φ	End (MJD)	Φ
N V	18:36:31	1767	50000.77536378	0.40	50000.80212738	0.55
Si III	20:09:49	1767	50000.84015545	0.76	50000.86692050	0.92
He II	21:46:05	1767	50000.90700730	0.14	50000.93377235	0.29
He II	23:22:35	408	50000.97402119	0.52	50000.98018583	0.56
Quiescence Obs. No. 2: 95/11/27						
N V	15:02:37	1767	50048.62682216	0.897	50048.65358866	0.04
Si III	16:38:29	1767	50048.69339624	0.27	50048.72015984	0.42
He II	18:14:59	1767	50048.76041157	0.65	50048.78717517	0.80
He II	19:51:29	408	50048.82742402	0.02	50048.83358866	0.06

A detailed observing log of the observations is given in Table 1 where we tabulate for each ion wavelength region the start time of the observation, the total exposure time in seconds, the start and end times in modified Julian Date (MJD) and the orbital phase at the start and end times of each exposure. For the phasing we adopted the orbital ephemeris

of Marsh et al. (1990) where phase 0.0 corresponds to inferior conjunction of the secondary star; viz.,

$$[\text{HJD}=32437638.82325 + 0.1769061911]$$

In this phase convention, the white dwarf would have maximum positive velocity at phase 0.75 and maximum negative velocity at phase 0.25. While the Si III and He II velocities during obs1 and obs2 are consistent with the expected motion of the white dwarf, the N V velocities are inconsistent with this motion. Therefore, the N V absorption features cannot be associated with the Einstein-redshifted rest frame of the white dwarf photosphere.

In Table 2 we present measurements of the strongest absorption features in the three wavelength regions. For the N V doublet and the five individual members of the Si III multiplet, we have tabulated the average of the individual velocities.

Table 2. Line measurements

Ion	λ (rest)	Obs1	$<\Phi>$	$<V1>$	Obs2	$<\Phi>$	$<V2>$
NV	1238.821	1238.98	0.48	+50	1239.62	0.96	+202
	1242.804	1243.05			1243.67		
Si III	1294.545	1295.56	0.84	+251	1294.87	0.35	+75
	1296.726	1297.93			1297.08		
	1298.946	1299.94			1299.23		
	1301.149	1302.23			1301.49		
	1303.322	1304.46			1303.65		
He II	1640.414	1640.78	0.22	+56	1641.52	0.73	+191

3. Surface Temperatures and Chemical Abundances During Quiescence

It is clear that with only three GHRS settings covering different 35 Å wavelength regions and different orbital phase ranges, synthetic spectral fitting will be less accurate than if the entire far UV spectrum were available. This disadvantage of the limited continuum is offset slightly by the detailed line profile information we have available. We have assumed no temporal changes occurred within each set of HST observations and fitted synthetic spectra to the three spectral regions simultaneously, for obs1 and obs2.

Our fitting attempt utilized both single temperature white dwarf models as well as combined white dwarf plus accretion belt synthetic fluxes. The details of our fitting procedure is the same as in our previous analyses and for the sake of brevity will not be repeated here (see Sion et al. 1996; Cheng et al. 1997).

Our best fitting single temperature white dwarf model yielded the values for obs1 and obs2 shown in Table 3.

Table 3. Results of White Dwarf Spectral Fitting

Parameter	Obs1 (13 Days POB)	Obs2 (61 days POB)
log g	8.0	8.0
T _{wd} (10 ³ K)	32.2	30.0
V _{rot} (km s ⁻¹)	100	120
Abundances (in units of Solar)		
C	0.05	0.05
Si	0.4	0.4
He	1.0	1.0
Others	1.0	1.0

The derived abundances are the first to indicate sub-solar values in the accreted atmosphere of the U Gem white dwarf. The C and Si abundances are significantly lower than the essentially solar abundances derived in earlier HST and HUT analyses at lower spectral resolution (Cheng et al. 1997; Long et al. 1993; Long et al. 1996), a point we return to in the concluding section. Note also that the magnitude of the heating and cooling is also reduced compared with earlier analyses (see section 4).

Two temperature fits were also attempted subject to the earlier caveats regarding the limited spectral coverage. The best results were achieved with white dwarf models having essentially the same temperatures as in Table 1, in combination with a rapidly spinning belt with $V_{belt} = 3,300 \text{ km s}^{-1}$ and $T_{belt} = 45\text{-}50,000 \text{ K}$. While these fits yielded slightly lower χ^2 values than the single white dwarf models, we found less agreement with the depths of the absorption line features, especially the Si III photospheric lines which are fit nearly perfectly by a slowly rotating single temperature white dwarf model.

4. The Gravitational Redshift Mass of the U Geminorum White Dwarf and Its Implications

In Table 2 we list the rest wavelengths, the observed wavelength measurements, the corresponding orbital phase at mid-exposure for each ion, and the corresponding velocities of N V , Si III, and He II for obs1 and obs2. The shift $\Delta\lambda$ is defined as $\lambda_{obs} - \lambda_{model}$.

The observed shifts for Si III and He II in both obs1 and obs2 are consistent in phase with the expected motion of the white dwarf. However the N V absorption shows a peculiar shift with $V = 202 \text{ km s}^{-1}$ near zero phase! We regard the Si III as completely photospheric in origin. However, given that He II may also be contributing from the same high temperature region as N V, (i.e. $T_{eff} > 80,000 \text{ K}$) it is unlikely to be entirely

photospheric and is therefore disregarded in the gravitational redshift determination. Given that Si III is Einstein-redshifted in the rest frame of the white dwarf and that its multiplet consists of 6 individually-resolved lines, we took an average of the individual transitions as the true global photospheric feature, and adopt it for a gravitational redshift determination. At mid-exposure phase 0.84 the Si III velocity is 251 km s^{-1} while at mid-exposure phase 0.35 the Si III velocity is 75 km s^{-1} .

Using Si III and assuming a sinusoidal relation to solve for K1, we find it is 107 km s^{-1} . At present there are two well-measured but discordant values of the gamma velocity of U Gem, 84 km s^{-1} (Wade 1981) and 43 km s^{-1} (Friend et al. 1993). Adopting the systemic velocity of Friend et al. (1993), viz., 43 km s^{-1} , we find that the gravitational redshift of the white dwarf is 118 km s^{-1} . Adopting the systemic velocity of Wade (1981), viz., 84 km s^{-1} , we find that the gravitational redshift of the white dwarf is 77 km s^{-1} . We do not know which is closer to being correct so we will take a mean of the two. If we take this mean gamma velocity, we find the resulting redshift is 99 km s^{-1} . It is quite remarkable that all three of these redshift values, when compared with the mass-radius relation from the extensive grid of evolutionary models by Wood (1996) for a carbon core, indicate a very massive white dwarf. While we cannot rule out an O-Ne-Mg core for the U Gem degenerate, the redshift yielded by using the Friend et al. value can almost certainly be ruled out because it implies a mass exceeding the Chandrasekhar mass. Even the mean value (62 km s^{-1}) yields a mass $\geq 1.2 M_{\odot}$! The Wade (1981) value however yields an entirely reasonable mass of $1.1 M_{\odot}$, a result in agreement with the optical spectroscopic radial velocity study of Stover (1981; see also Zhang and Robinson 1987) which yielded a white dwarf mass of $1.18 M_{\odot}$. Furthermore Webbink's critical systematic re-determination of CV white dwarf masses yielded a value for the U Gem white dwarf of $\sim 1.1 M_{\odot}$.

5. Heating and Cooling of the White Dwarf

It is surprising that the white dwarf T_{eff} values 13 days and 61 days after outburst are cooler T_{eff} measurements at comparable times after outburst than previous studies. This is supported by a lower flux level of our GHRS spectra (by 4×10^{-14}) compared with all other post-outburst temperature measurements at comparable times in quiescence (e.g. Sion et al. 1994; Long et al. 1993, 1994, 1995). Our observations and the FOS observations of Long et al. 1994 were both obtained following a narrow outburst of U Geminorum. Since we expect that the amount of heating of the white dwarf and the subsequent rate of cooling should be similar following the same types of outburst, then it is clear that the white dwarf T_{eff} 13 days POB (32,000K) is considerably lower than the value (39,000K) measured 13 days after the narrow outburst of U Gem reported by Long et al. (1994). We believe the T_{eff} difference is real and is almost certainly related to the extraordinarily long quiescence experienced by U Gem in 1994/95 , which was ended after 210 days by a wide outburst in April 1995 , then a short 68 day quiescence followed by the narrow outburst preceding our observations (see Fig.1). The normal quiescent interval of U Gem is 118 days (Szkody & Mattei 1984). Long et al. (1996) reported a T_{eff} of 29,000K 185 days into the long 210 day quiescence. Since that quiescence lasted another 25 days, it is even possible that some additional cooling of the white dwarf took place. Therefore, if the white dwarf had cooled down to 27-29,000K, the compressional heating calculations of Sion (1995) at a rate $\dot{M} = 10^{-8} M_{\odot} \text{ yr}^{-1}$ for 7 days would predict a peak heating of only $\sim 35,000\text{K}$ at the exact end of the outburst and a subsequent cooling down to $\sim 27,000\text{K}$ which is not too far below the estimated T_{eff} at 185 days POB by Long et al. (1994). In this scenario, the long quiescence could have disrupted a normal time-averaged "equilibrium" between accretional heating of the upper envelope and cooling by radiation. The normal (average) equilibrium would be re-established only after a sufficient number of dwarf nova cycles.

On the other hand, the long (210 day) quiescence could have led to a complete or nearly complete spin down of differentially rotating white dwarf surface layers (e.g. an accretion belt; see Cheng et al. 1997). Hence, subsequent accretion events during the following wide and narrow outbursts would have deposited mass and energy with a percentage-wise greater dissipation in the boundary layer, thus resulting in a greater proportion of the accretion energy being released at soft X-ray/EUV wavelengths. This may account for the lower surface temperature we observe post-outburst and would directly manifest a dependence of the heating of the white dwarf on the accreting star’s short term angular momentum history.

6. Implications of the White Dwarf Chemical Abundances

If the white dwarf accretes solar or nearly solar C, then C must rapidly gravitationally settle out of its atmosphere. This leads to two major conflicts. Why don’t the other metals also gravitationally settle out and why is the C abundance the same sub-solar value at 13 and 61 days after the dwarf nova outburst? For example, ongoing accretion of a solar mix of gas during quiescence would quickly replenish diffusion-depleted C. There is another possible solution: an ancient thermonuclear runaway (TNR).

It is fully expected that U Gem and all other dwarf novae will undergo (and have undergone in the past) a TNR when the WD has accumulated sufficient hydrogen-rich material (Starrfield, Sparks and Shaviv 1988). During a TNR, C proton captures to form N. If the C abundance is larger than solar, then a strong TNR results, leading to a nova outburst (Starrfield 1995) . This C overabundance comes from the accreted material mixing with the white dwarf’s core material (Starrfield, Truran, Sparks and Kutter 1972) Thus, most observations of novae end up with an overabundance of C, even though much of the C

has been processed to N. If there is no mixing with the core, then in most cases the TNR will be weak. The notable exception is a rapidly accreting, very high mass WD ($\sim 1.35 M_{\odot}$), which is associated with recurrent novae (Sparks, Kutter, Starrfield and Truran, J. 1990) . For a more slowly accreting WD (as in the case of a dwarf novae, or a less massive WD), the TNR will be weaker, little or no material will be ejected during the outburst, and a large common envelope will form. Although some of the common envelope may be ejected, a fraction will be deposited on the secondary and a similar fraction will be consumed by the white dwarf's rekindled H shell source. This shell source will leave a He-rich material layer enriched in N and depleted in C. This He layer should prevent core material from being mixed up, thus leading to subsequent weak TNRs. Later dwarf novae will deposit C depleted material due to the TNR and common envelope to be mixed with even stronger C depleted WD material due to the TNR and the remnant H shell burning source. Thus C will be depleted and the N will be enhanced in both the accreted material and the WD's surface material. We did not cover any photospheric N lines in our GHRS setting with which to obtain an N abundance but our prediction is that N should be overabundant in U Gem.

A number of our HST observations of U Gem support or are, at least, consistent with this scenario. First, the very slow WD's rotation velocity and very low C abundance are indicators that not much material has been accreted since the last TNR. Both the C abundance and the rotational velocity will increase with the amount of accreted material. Second, the large WD mass means that the amount of accreted mass needed to trigger TNR will be small. The small accreted mass implies that the accretion timescale will also be short. A short accretion timescale works against two of the four proposed mixing mechanisms: accretion-driven shear mixing and diffusion (Livio 1993). The weaker TNR from the low initial C abundance hinders the other two mechanisms (convection-driven shear mixing and undershooting) from penetrating the remnant He layer. If this scenario is

correct it means that U Gem and probably other dwarf novae are massive WDs increasing in mass with the possibility of becoming a SNI.

7. Concluding Remarks

Using GHRS G160M spectroscopic observations, we have uncovered surprises in further characterizing the physical characteristics of the white dwarf in U Gem and its response to heating by the dwarf nova outburst. The markedly lower elevation of white dwarf surface temperature we have measured, compared to previous observations, is probably related to the very long quiescent interval preceding the two following outbursts. Since the Kelvin time of the heated upper envelope is of order 1-3 months, then the 210 day cooling interval could have led to a disruption of the time-averaged temperature equilibrium between accretional heating and radiational cooling. We have also uncovered the first evidence for subsolar metal abundances in U Gem, with C markedly depleted by 0.05 with respect to the solar value, precisely what is expected to be the processed aftermath of a C-depleting, N-enriching CNO thermonuclear runaway.

We confirm the low white dwarf rotational velocity derived in an earlier GHRS study (Sion et al. 1994) and find little spectroscopic evidence to support an accretion belt on the white dwarf following outburst. The N V absorption lines are clearly not associated with a formation in the white dwarf photosphere. Our GHRS Si III data obtained near the orbital quadratures have provided a white dwarf velocity semi-amplitude of 107 km s^{-1} and a gravitational redshift of 77 km s^{-1} which corresponds to a white dwarf mass of $1.1 M_{\odot}$, if the core is made of carbon. A mass value this high for the U Gem degenerate is supported by mass determinations based upon the velocity amplitudes of disk emission lines (Stover 1981; Webbink 1990). This high value is also not unexpected for a CV degenerate above the period gap and suggests that, if core mass erosion proceeds with each nova outburst,

then the U Gem degenerate must be relatively young or its mass would have been lowered. On the other hand, if the core does not erode, then a lower limit to the age of the system as a CV is the white dwarf cooling time (Sion 1991). The lowest T_{eff} measured for the white dwarf is $T_{eff} = 27,000\text{K}$ (Long et al. 1996) yielding a lower limit of 5×10^7 years for the age of U Gem as a CV.

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Figure Captions

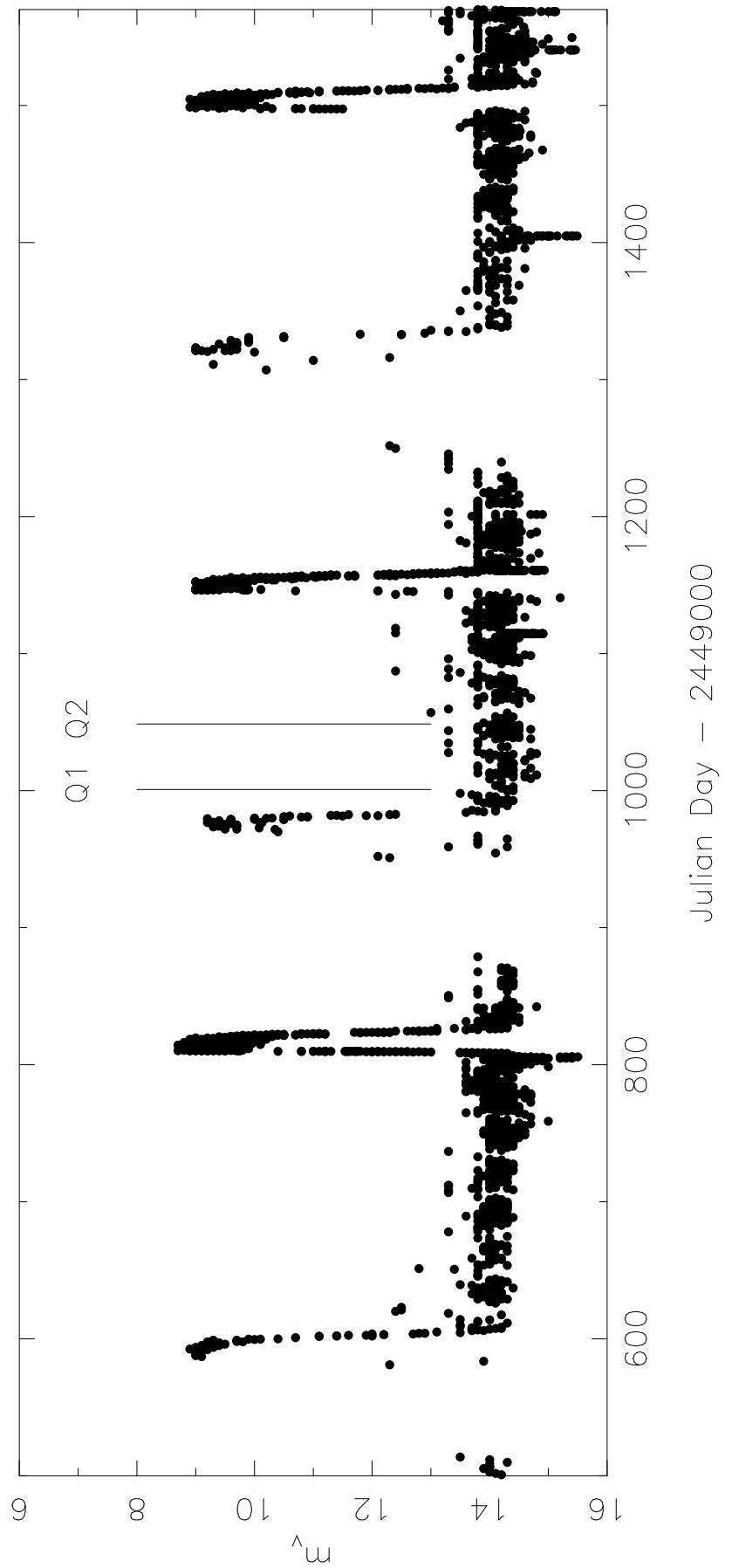
Fig. 1 - The AAVSO light curve data (visual magnitude versus time) showing the placement of the HST observations during quiescence.

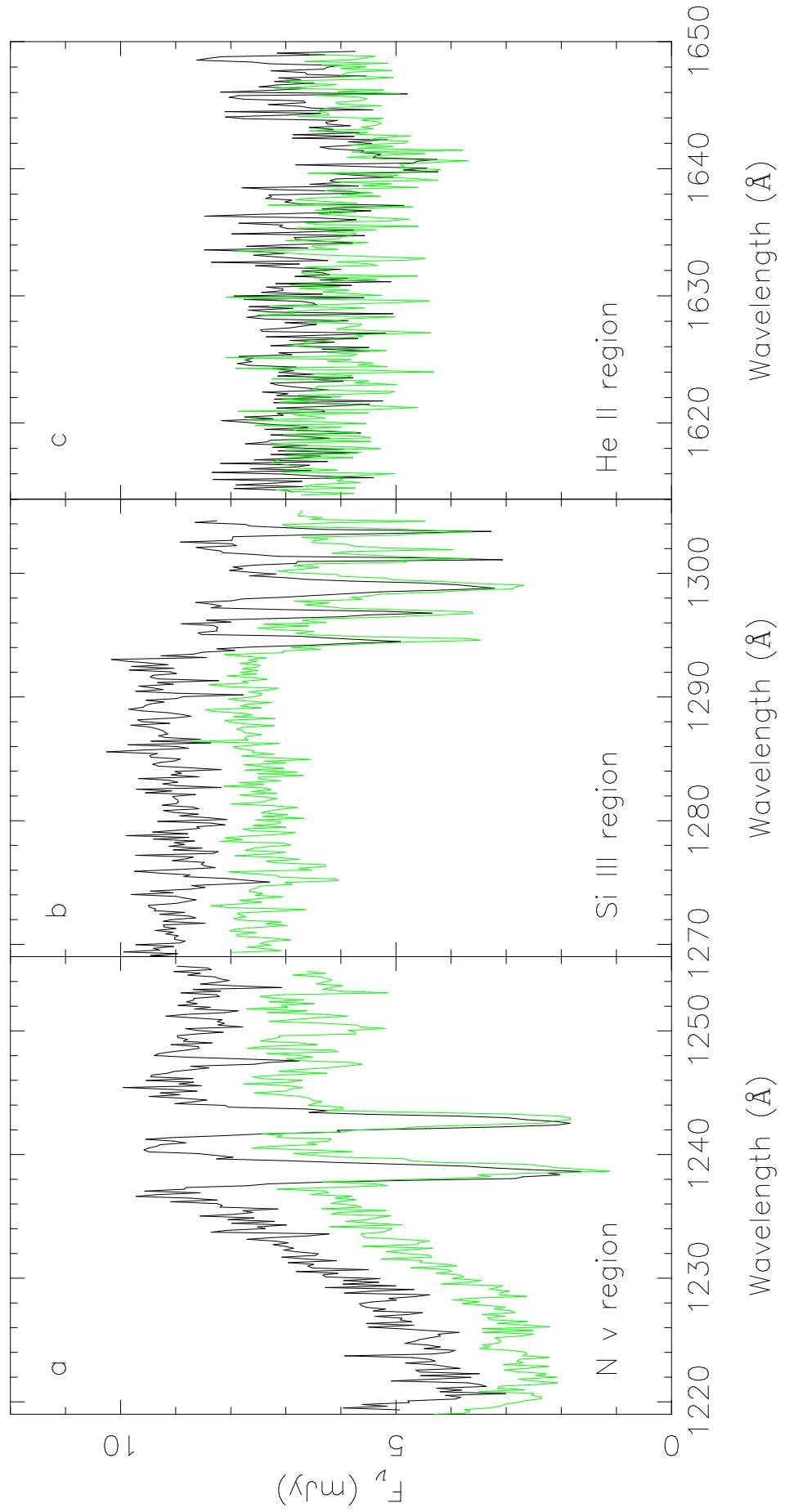
Fig. 2 - The GHRS observations of U Gem in the regions of N V (1238Å, 1242Å), Si III (1300 Å), and He II (1640 Å) during obs1 (the solid curve) and during obs2 (the dotted curve), displayed as flux F_ν (mJy) versus wavelength (see text for details).

Fig. 3 - The best rotating white dwarf model fit to the three combined GHRS wavelength regions at 13 days post-outburst (top panel). The model fluxes are shown in bold face and span the wavelength range 1150 Å to 1650 Å while the limited range of the three GHRS spectra are shown with a lighter shade. The individual GHRS G160M regions for N V, Si III and He II are shown in the bottom panels. Note that the observed N V features cannot be accounted for by the white dwarf fluxes. Note also the photospheric C III λ 1247 absorption feature just longward of N V λ 1242.

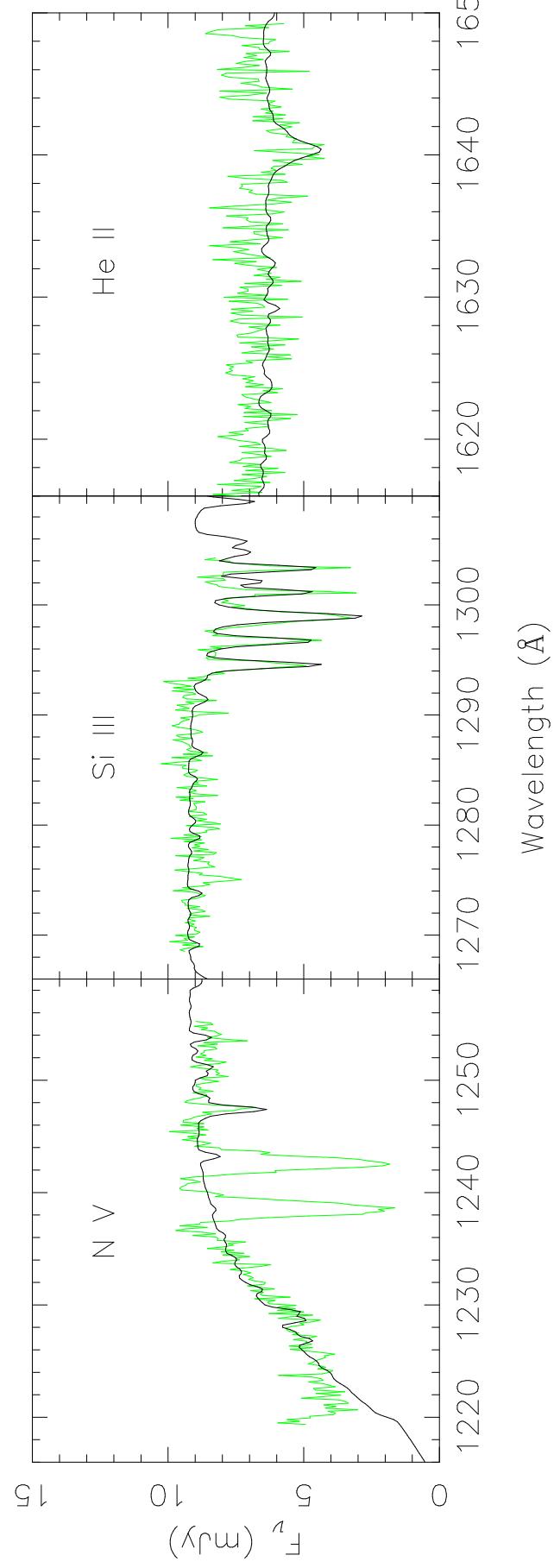
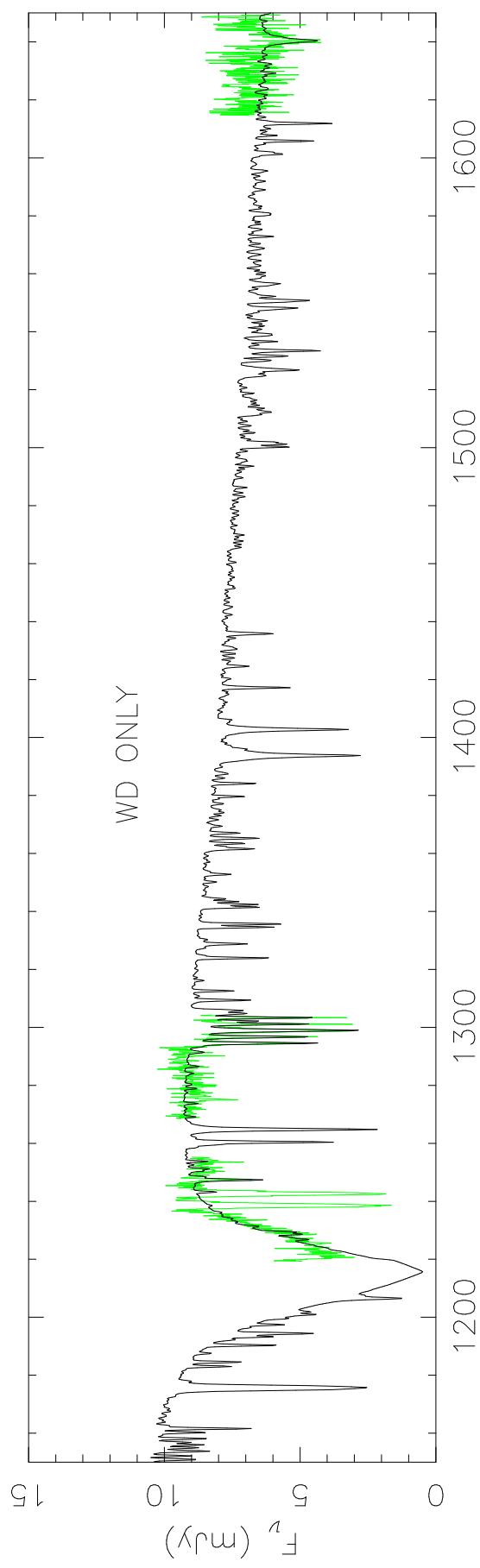
Fig. 4 - The same as Fig. 3, but for the observations at 61 days post-outburst.

U Gem at quiescence





U Gem: 13 days post-outburst



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U Gem: 61 days post-outburst

